Chapter 7

Delaware Estuary Case Study

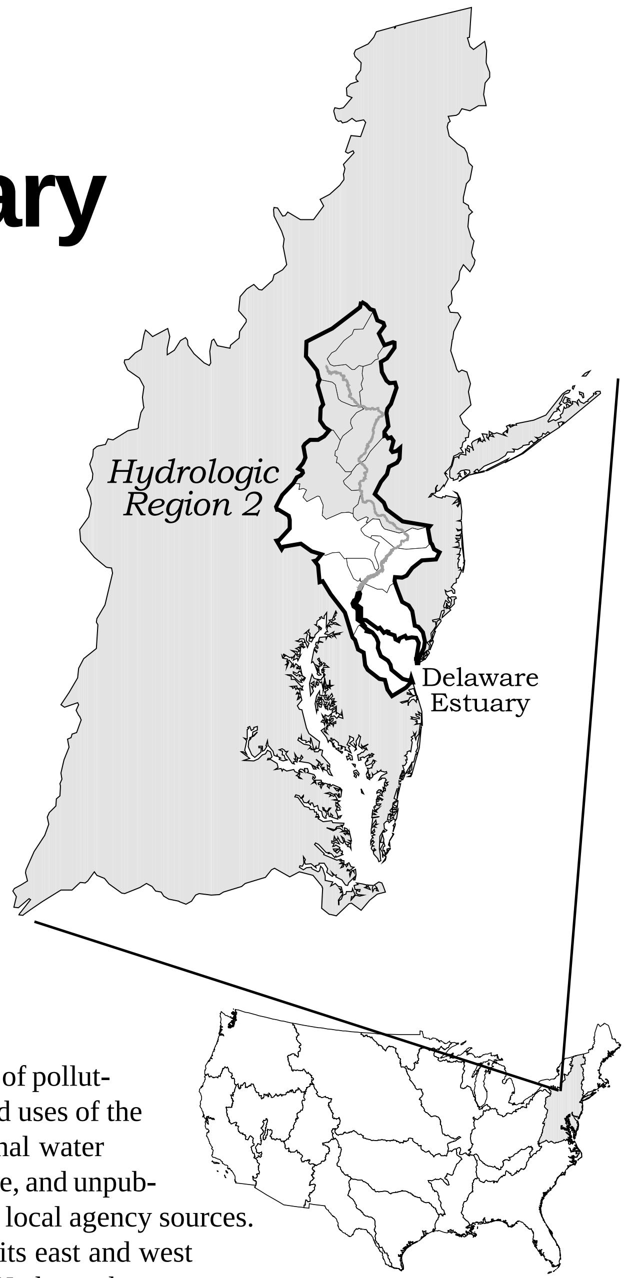


Figure 7-1
Hydrologic Region 2 and Delaware estuary watershed.

The Mid-Atlantic Basin (Hydrologic Region 2), covering a drainage area of 111,417 square miles, includes some of the major rivers in the continental United States. Figure 7-1 highlights the location of the basin and the Delaware estuary, the case study watershed profiled in this chapter.

With a length of 390 miles and a drainage area of 11,440 square miles, the Delaware River ranks 17th among the 135 U.S. rivers that are more than 100 miles in length. On the basis of mean annual discharge (1941-1970), the Delaware ranks 28th (17,200 cfs) of large rivers in the United States (Iseri and Langbein, 1974). Urban-industrial areas in the watershed caused severe water pollution problems during the 1950s and 1960s (see Table 4-2). This chapter presents long-term trends in population, municipal wastewater infrastructure and effluent loading of pollutants, ambient water quality, environmental resources, and uses of the Delaware Estuary. Data sources include USEPA's national water quality database (STORET), published technical literature, and unpublished technical reports ("grey" literature) obtained from local agency sources.

The Delaware River, formed by the confluence of its east and west branches in the Catskill Mountains near Hancock, New York, on the Pennsylvania-New York state line, becomes tidal at Trenton, New Jersey (Figure 7-2). The first 86 miles of the tidal river are the Delaware River estuary, which flows by Trenton, New Jersey; Philadelphia, Pennsylvania; Camden, New Jersey; and Wilmington, Delaware. This major urban-industrial area has a tremendous impact on the water quality of the river. In this area, the Delaware River estuary flows along the boundary between the Piedmont Plateau and the Atlantic Coastal Plain. A large number of municipal and industrial wastewater facilities discharge to the Delaware River, with municipal water pollution control plants accounting for the largest component of BOD_5 loading. In general, water quality is good at the head of the tide at Trenton (RM 134.3), but it begins to deteriorate downstream.

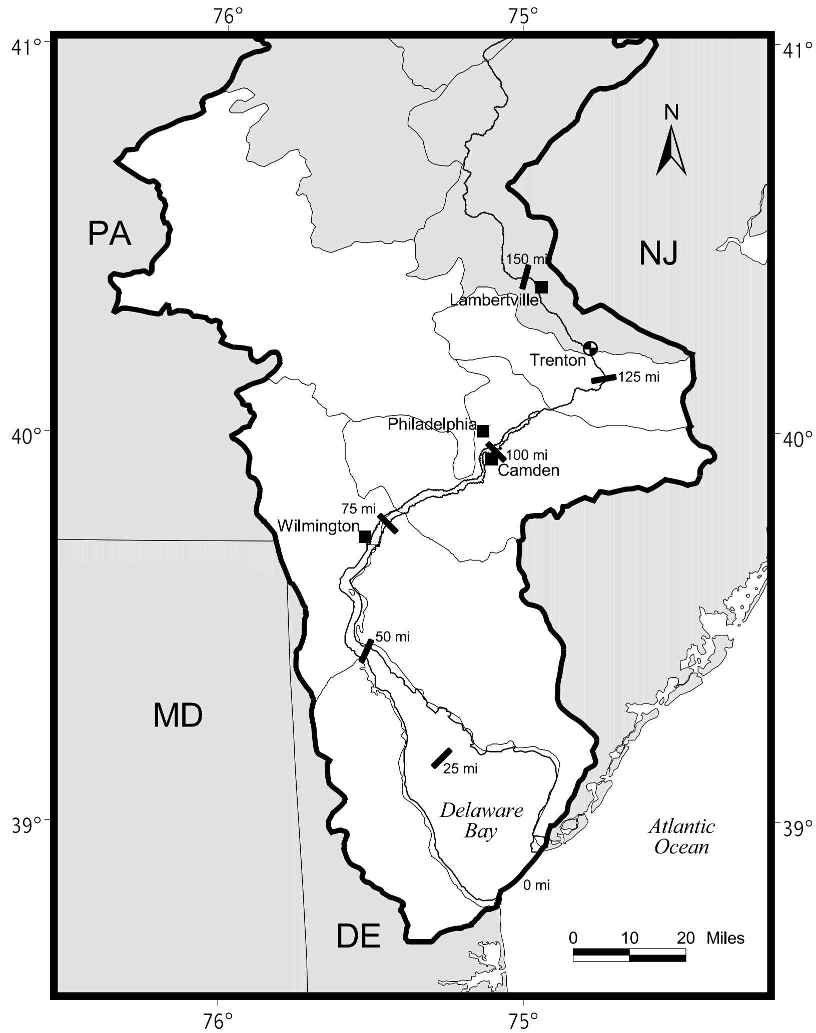


Figure 7-2

Location map of the Lower Delaware River-Delaware Bay. (River miles shown are distances from the Cape May, NJ, to Cape Henlopen, DE, transect.)

From the 1930s through the 1970s, water quality conditions were very poor. Depleted DO levels were recorded in the region from Torresdale (RM 110.7) to Eddystone (RM 84.0) as a result of wastewater loading from Philadelphia (RM 110-93). Since the mid-1980s water quality conditions in the estuary have improved significantly.

Physical Setting and Hydrology

The Delaware River originates in the south-central area of New York State and flows 390 miles in a southerly direction to the Atlantic Ocean, separating New Jersey on its eastern bank from Pennsylvania and Delaware on its west. The total drainage area at the mouth of the river at Liston Point on Delaware Bay is 11,440 square miles, of which 6,780 square miles lie above the gaging station at Trenton, New Jersey (Iseri and Langbein, 1974). The major tributary to the Delaware Estuary is the Schuylkill River, which joins the main stream in the vicinity of Philadelphia, Pennsylvania. The Schuylkill has a drainage area of 1,890 square miles at the Fairmount Dam, 8 miles above the mouth. In addition to the

Schuylkill River, the other major tributaries to the Delaware estuary include Assunpink Creek, Crosswicks Creek, Rancocas Creek, Neshaminy Creek, Cooper River, Chester Creek, the Christina River, and the Salem River. Figure 7-3 presents long-term statistics of summer streamflow from the USGS gaging station at Trenton, New Jersey, from 1940 to 1995. The extreme drought conditions of the mid-1960s are quite apparent in the long-term record (1962-1966). Seasonal variation of freshwater flow of the Delaware River is characterized by high flow from March through May, with a peak flow of 21,423 cfs in April. Low-flow conditions typically occur from July through October, with the monthly minimum flow of 5,830 cfs recorded during September (Figure 7-4). From July through October, low-flow in the river is typically augmented by releases from reservoirs. During dry conditions, reservoir releases, regulated to maintain a minimum flow of 2,500-3,000 cfs at Trenton, can be greater than 60 percent of the inflow to the estuary (Albert, 1997).

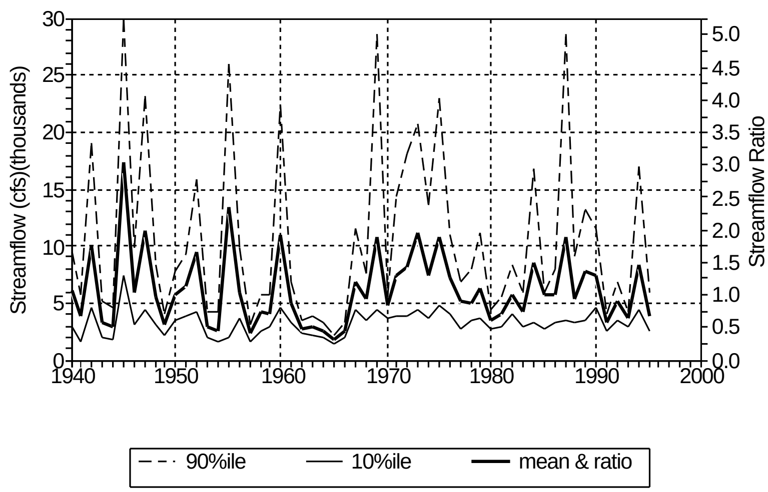


Figure 7-3

Long-term trends in mean, 10th, and 90th percentile streamflow in summer (July-September) for the Delaware River at Trenton, NJ (USGS Gage 01463500).

Source: USGS, 1999.

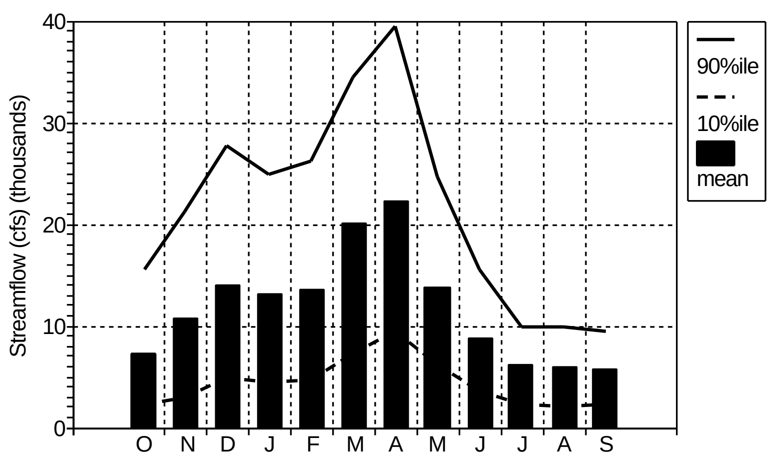


Figure 7-4

Monthly trends of mean, 10th, and 90th percentile streamflow for the Delaware River at Trenton, NJ (USGS Gage 01463500), 1951-1980.

Source: USGS, 1999.

The Delaware River-Delaware Bay system is one of the major coastal plain estuaries of the east coast of the United States. The tidal river and estuary extend a distance of 134 miles from the fall line at Trenton, New Jersey, to the ocean mouth of Delaware Bay along an 11-mile section from Cape May, New Jersey, to Cape Henlopen, Delaware (Figure 7-1). Because Philadelphia is a major east coast port, a navigation channel is maintained to a depth of 12 meters (39 feet) from the entrance to the bay upstream to Philadelphia. From Philadelphia to Trenton, the channel is maintained at a depth of 8 meters (26 feet) (Galperin and Mellor, 1990). The semidiurnal tide has a mean range of 1.5 meters (4.9 feet) at the mouth of the bay and propagates upstream on the incoming tide to Trenton in approximately 7 hours; typical tidal currents are approximately 1.5 meter sec^{-1} (Galperin and Mellor, 1990). Approximately 25 miles downstream from Philadelphia, tidal currents near the Tacony-Palmyra Bridge (RM 107) are characterized by vigorous vertical mixing and a marked current reversal with currents of approximately 1.0 meter sec^{-1} (Thomann and Mueller, 1987).

The Delaware estuary can be characterized as three distinct hydrographic regimes based on distributions of salinity, turbidity, and biological productivity: (1) tidal freshwater, (2) transition zone, and (3) Delaware Bay zone. The tidal fresh river extends about 55 miles from the head of tide at Trenton, New Jersey (RM 134) to Marcus Hook, Pennsylvania (RM 79). Under mean freshwater flow conditions, salinity intrusion in the tidal fresh section of the river generally extends upstream to the reach between the Delaware Memorial Bridge at Wilmington (RM 68.7) and Marcus Hook (RM 79.1). During drought periods (e.g., 1962-1966), salinity intrusion is a concern because industrial water withdrawals are less desirable and recharge areas of the South Jersey aquifers serving the Camden metropolitan area are potentially threatened (DRBC, 1992). During drought conditions, the Delaware River Basin Commission requires releases from the upper basin reservoirs to prevent critical salinity concentrations from intruding farther upstream than Philadelphia at RM 98 (DRBC, 1992). The transition zone, extending about 26 miles from Marcus Hook (RM 79) to Artificial Island, New Jersey (RM 53), is characterized by low salinity levels, high turbidity, and relatively low biological production (Marino et al., 1991). The estuarine region extends downstream of Artificial Island about 53 miles to the mouth of Lower Delaware Bay; salinity in this region varies from approximately 8 ppt upstream to approximately 28 ppt at the mouth of the bay (Marino et al., 1991).

Population, Water, and Land Use Trends

Four densely populated metropolitan areas have developed along a 50-mile industrialized section of the Delaware River from Philadelphia, Pennsylvania, and Trenton and Camden, New Jersey, to Wilmington, Delaware. From 1880 to 1980, urban growth accounted for most of the 236 percent increase in total population of the region. The urban proportion of the population increased from approximately 64 percent at the turn of the century to approximately 80 percent in 1980 (Marino et al., 1991). During the period after World War II from 1950 through 1980, development in the region was characterized by urban and suburban sprawl: urban land use area increased from 460 square miles in 1950 to 3,682 square miles by 1980 while population density declined from 8,000 to 3,682 persons per square mile (Marino et al., 1991). Much of this development occurred by converting agricultural lands in close proximity to the major metropolitan areas to suburban land uses.

The Delaware River case study area includes 14 counties identified by the Office of Management and Budget (1995) as the Philadelphia-Wilmington-Atlantic City, PA-NJ-DE-MD Metropolitan Statistical Area (CMSA) (Table 7-1). Long-term population trends from 1940 through 1996 for these counties are presented in Figure 7-5. Population in these counties has increased by 162 percent from 3.67 million in 1940 to 5.97 million by 1996 (Forstall, 1995; USDOC, 1998).

The city of Philadelphia withdraws water for domestic water supply at the Torresdale intake upstream of the salt front. The city of Trenton also withdraws water for public water supply from the Delaware River. In addition to these cities, Camden, the Delaware County Sewer Authority, and Wilmington are among more than 80 dischargers of municipal wastewater directly to the estuary or the tidal portions of its tributaries. Historical water use data are not readily available at the county level of aggregation to assess the contribution of the Delaware estuary

Table 7-1. Metropolitan Statistical Area (MSA) counties in the Delaware Estuary case study. *Source: OMB, 1999.*

Philadelphia-Wilmington-Atlantic City, PA-NJ-DE-MD CMSA	Atlantic, NJ	Chester, PA
	Cape May, NJ	Delaware, PA
	Burlington, NJ	Montgomery, PA
	Camden, NJ	Philadelphia, PA
	Gloucester, NJ	Cumberland, NJ
	Salem, NJ	New Castle, DE
	Bucks, PA	Cecil, MD

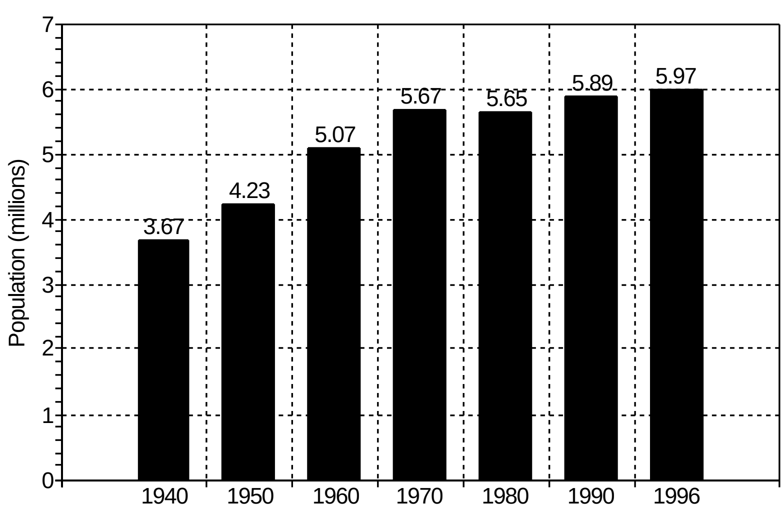


Figure 7-5

Long-term trends in population for the Philadelphia-Wilmington-Atlantic City MSA counties of the Lower Delaware River-Delaware Bay.

Source: Forstall, 1995; USDOC, 1998.

region. However, long-term trends for municipal and industrial water withdrawals have been compiled by the USGS for the entire Middle-Atlantic Basin from 1950 to 1995 (e.g., Solley et al., 1998). The natural resources (plankton, fisheries, marshes, and shorebirds), human uses (waste disposal, transportation and dredging, beach development), and management issues of the Delaware estuary are presented in Bryant and Pennock (1988).

Historical Water Quality Issues

In reports sent back to Europe, Captain Thomas Young, one of the early explorers of the Delaware estuary, noted that "*the river aboundeth with beavers, otters and other meaner furrs . . . I think few rivers of America have more . . . the quantity of fowle is so great as hardly can be believed. Of fish heere is plentie, but especially sturgeon.*" Early colonial advertising copy like this, circulated widely in Europe, presumably inspired Old World colonists to emigrate to the Delaware Valley (Sage and Pilling, 1988). The estuary was abundant with striped bass, sturgeon, shad, oysters, and waterfowl.

Beginning with the Industrial Revolution and the development of the Delaware Valley as a major industrial and manufacturing center in the 19th century, waste disposal from increasing population and industrial activities resulted in progressive degradation of water quality and loss of the once-abundant natural resources of the estuary. By the turn of the century, the American shad population had collapsed. By 1912-1914, low DO conditions were all too common in the Philadelphia and Camden area of the river (Albert, 1997). Sanitary surveys conducted in 1929 and 1937 documented poor water quality conditions in the nontidal reaches of the Delaware from Port Jervis, New York, to Easton, Pennsylvania. During high-flow conditions, black water from the Lehigh River-Easton area would result in closing of the water supply intakes at Trenton, New Jersey (Albert, 1982).

In the tidal river between Trenton and Philadelphia, the discharge of raw sewage from Philadelphia, Trenton, Camden, Wilmington, and other communities, along with untreated industrial wastewater discharges, resulted in gross water pollution of the estuary. Peak densities of approximately 6,000-8,000 MPN/100 mL were recorded during the late 1960s and early 1970s in the vicinity of the Philadelphia Navy Yard (RM 90) (Patrick et al., 1992; Marino et al., 1991). Fecal coliform bacteria levels were high as a result of raw or inadequately treated wastewater discharges from the large municipalities. Acidic conditions from industrial waste discharges were observed in the river near the Pennsylvania-Delaware border; pH levels ranged from approximately 6.5 to 7.0 during 1968-1970 in the section of the river from Paulsboro (RM 89) to the Delaware Memorial Bridge (RM 68) (Marino et al., 1991). During the summer months in the 1940s, 1950s, and 1960s, DO levels were typically approximately 1 mg/L or less over a 20-mile section of the river from the Ben Franklin Bridge in Philadelphia (RM 100) to Marcus Hook (RM 79). Under these anoxic and hypoxic conditions, the urban-industrial river ran black, and the foul stench of hydrogen sulfide gas was a common characteristic (Patrick, 1988). Dock workers and sailors were often overcome by the stench of the river near Philadelphia, and ships suffered corrosion damage to their hulls from the polluted waters. Aircraft pilots landing in

Philadelphia reported smelling the Delaware estuary at an altitude of 5,000 feet. Water quality conditions were so bad that President Roosevelt ordered a study in 1941 to determine whether water pollution in the river was affecting the U.S. defense buildup (Albert, 1982; CEQ, 1982).

Legislative and Regulatory History

Water pollution in the Delaware reached its peak in the 1940s. The source of the pollution was raw sewage (350 mgd from Philadelphia alone), along with untreated industrial wastewater of all kinds. In response to steadily increasing pollution, the Interstate Commission on the Delaware River Basin (INCODEL) launched a basinwide water pollution control program in the late 1930s. Following a delay due to the war, the abatement program was finally completed by the end of the 1950s. During that time the number of communities with adequate sewage collection and treatment facilities rose from 63 (approximately 20 percent) to 236 (75 percent) (Albert, 1982). Concurrent success was not achieved in abating industrial pollution.

The first generation of water pollution control efforts, largely completed by 1960, resulted in secondary treatment levels at most treatment plants above Philadelphia. Primary treatment was considered adequate in the estuary below Philadelphia. Although most areas built the required facilities, some treatment facilities from the first-generation effort were not completed until the 1960s or 1970s.

In 1961 INCODEL became incorporated into a more powerful interstate regulatory agency, the Delaware River Basin Commission (DRBC). The DRBC, created as a result of federal and state legislation, has broad water resources responsibilities, including water pollution control. The Commission developed a clean-up program based on a 6-year $1.2 million Delaware Estuary Comprehensive Study (DECS) conducted by the U.S. Public Health Service. Nearly 100 municipalities and industries were found to be discharging harmful amounts of waste into the river. The DRBC calculated the river’s natural ability to assimilate oxidizable wastewater loads and established allocations for each city and industry (Thomann, 1963; Thomann and Mueller, 1987). The objective of the DRBC wasteload allocation program and the corollary programs of Pennsylvania, New Jersey, Delaware, and the federal government was to upgrade the somewhat improved water quality of 1960 to more acceptable levels.

For the purposes of water quality management, the Delaware estuary has been divided into six water quality zones. Zone 1 is above the fall line at Trenton, New Jersey. Zones 2 through 6 are in the tidal Delaware, which is water quality-limited. Here, more stringent effluent limits are required, based on allocations of assimilative capacity, to achieve water quality standards. Based on the DECS model, the DRBC in 1967 adopted new, higher water quality standards and then in 1968 issued wasteload allocations to approximately 90 dischargers to the estuary. These required treatment levels were more stringent than secondary treatment as defined by EPA in the 1972 Clean Water Act.

Impact of Wastewater Treatment: Pollutant Loading and Water Quality Trends

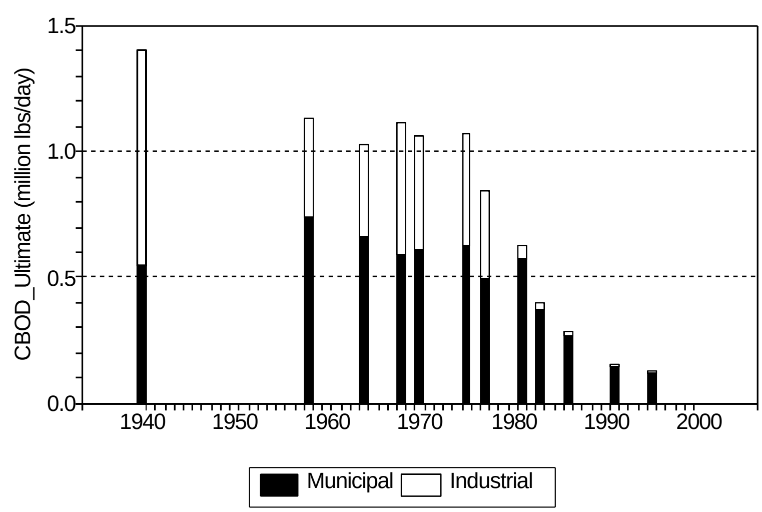
The Delaware River from Trenton, New Jersey, to Liston Point is one of the most heavily industrialized sections of a waterway in the United States. Four major cities and a large number of oil refineries and chemical manufacturing plants are located along the river. The effect of the DRBC wasteload allocation program and the related water pollution control programs of Pennsylvania, New Jersey, Delaware, and the federal government on the Delaware Estuary is best demonstrated by the substantial reduction of ultimate CBOD loading from municipal and industrial dischargers that has been achieved since the late 1950s (Figure 7-6). Ultimate CBOD loadings to the estuary have been reduced by 89 percent from 1,136,000 lb/day in 1958 (Patrick et al., 1992) to 128,277 lb/day by 1995 (HydroQual, 1998). Major wastewater treatment facilities that upgraded to secondary treatment and better to meet the wasteload allocations include Philadelphia NE (1985), Philadelphia SE (1986), Philadelphia SW (1980), CCMUA (1989), Trenton (1982), Bordentown MUA (1991), and Lower Bucks MA (1980). A complete listing of the 34 municipal and 26 industrial point sources discharging to the Delaware estuary between Trenton and Liston Point is presented by HydroQual (1998). In addition to reductions of pollutant loading from direct dischargers to the estuary, the cleanup of major tributaries to the Delaware has also contributed to water quality improvements in the Delaware estuary (Albert, 1982).

Since implementation of the 1972 CWA, reductions in point source loads of oxidizable materials have been achieved as a result of technology- and water quality-based effluent controls on municipal and industrial dischargers in the Delaware River watershed. Nonpoint source runoff, driven by the land uses and hydrologic characteristics of the watershed, also contributes a pollutant load that must be considered in a complete evaluation of the impact of regulatory policy and controls on long-term water quality trends. To evaluate the relative signifi-

Figure 7-6

Long-term trends in ultimate CBOD loading from municipal and industrial wastewater dischargers to the Delaware estuary.

Sources: HydroQual, 1998; Patrick et al., 1992.



cance of point and nonpoint source pollutant loads, inventories of NPDES point source dischargers, land uses, and land use-dependent export coefficients (Bondelid et al., 1999) have been used to estimate catalog unit-based point source (municipal, industrial, and CSOs) and nonpoint source (rural and urban)[1] loads of BOD_5 for mid-1990s conditions in the catalog units of the Delaware River case study area (see Figure 7-2). The point source load of 105.4 metric tons/day accounts for 89 percent of the total estimated BOD_5 load of 117.1 metric tons/day from point and nonpoint sources. Municipal facilities contribute 57.3 metric tons/day (49 percent) while industrial dischargers account for 47.5 metric tons/day (40 percent) of the total point and nonpoint source BOD_5 load (Figure 7-7). Nonpoint sources of BOD_5 account for 12.6 metric tons/day; rural runoff contributes approximately 8 percent and urban land uses account for approximately 5 percent of the total point and nonpoint load of 117.1 metric tons/day (Figure 7-7).

One of the major trends indicative of water quality improvement in the estuary has been that for DO. A comparison of mean summer DO levels between 1968-1972, 1975-1979, 1981-1985, and 1988-1994 (Figure 7-8) clearly shows the water quality improvements achieved as a result of the point source loading reductions of ultimate BOD_5 (Figure 7-6). Mean summer DO concentrations have increased by approximately 1 mg/L between River Mile 110 and River Mile 55 (DRBC Zones 3, 4, and 5) between 1957-1961 and 1981-1985 (Brezina, 1988). DO concentrations have increased from less than 2 mg/L to 5 mg/L at the critical DO sag point at the mouth of the Schuylkill River in Philadelphia (RM 92) during the period from 1968-1972 to 1988-1994. DO concentrations increased steadily farther downstream of Philadelphia (RM 83), reaching a level of approximately 5.5 mg/L during 1988-1994.

The historical summer DO spatial transects data (Figure 7-8) show that wastewater discharges from the Philadelphia area result in minimum DO conditions between the Ben Franklin Bridge (RM 100), the Philadelphia Navy Yard (RM 93), and Marcus Hook (RM 78). Figure 7-9 shows long-term summer (July-

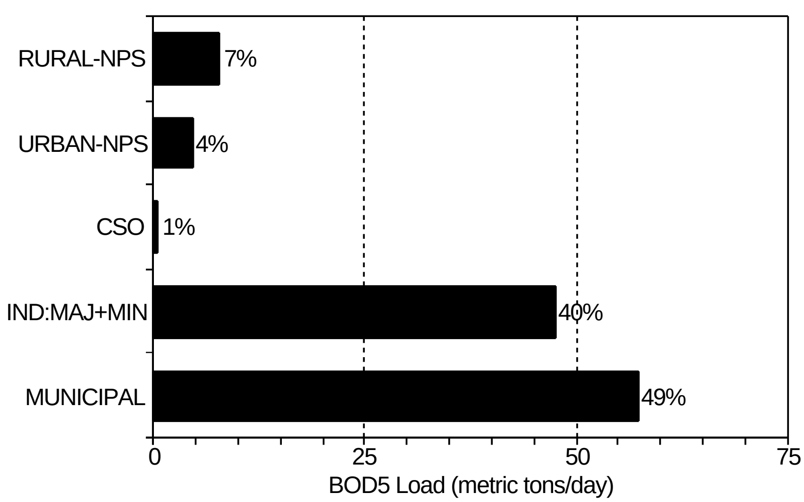


Figure 7-7

Point and nonpoint source loads of BOD_5 (ca. 1995) for the Lower Delaware River-Delaware Bay case study area.

Source: Bondelid et al., 1999.

[1] For purposes of this comparison, urban stormwater runoff includes areas both outside (termed "nonpoint sources") and within (which meet the legal definition of a point source in section 502(14) of the CWA) the NPDES stormwater permit program.

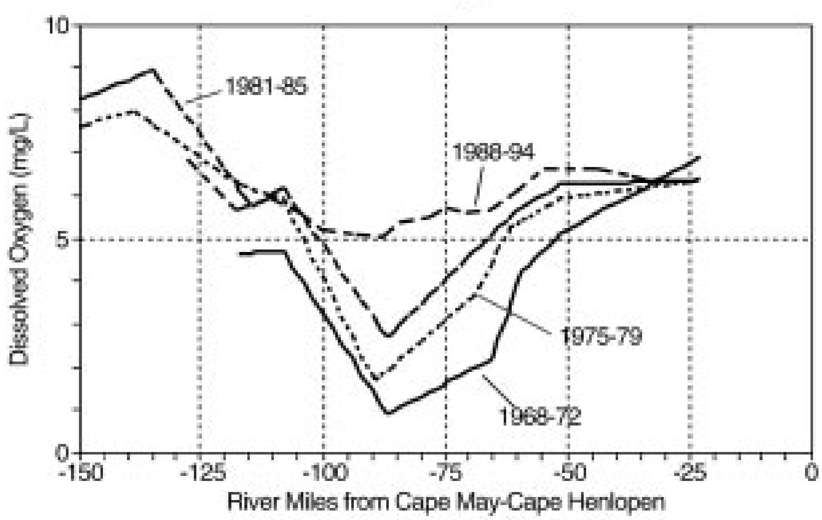


Figure 7-8

Long-term trends of the spatial distribution of summer DO in the Delaware estuary.

Source: Patrick et al., 1992; Scally, 1997.

September) trends in DO measured at stations within the reach from the Ben Franklin Bridge to the Philadelphia Navy Yard. The long-term trend documents improvements in oxygen during the 1980s and 1990s from the water pollution control efforts initiated during the 1970s. Most dramatic, however, is the progressive improvement in the minimum oxygen levels during the 1980s and early 1990s. Summer minimum values increased from approximately 1 mg/L or less in the 1960s and 1970s to approximately 4-5 mg/L during 1990-1995. Although oxygen conditions improved tremendously between the 1960s and the early 1990s, a continued trend of further improvements during the 1990s has not been recorded. Minimum oxygen concentrations still can approach 4 mg/L near Chester, Pennsylvania (River Mile 84) and can drop lower than 4 mg/L in the 10-mile oxygen sag reach between River Mile 95 and River Mile 85 (HydroQual, 1998).

Spatial water quality trends recorded during the late 1960s, 1970s, 1980s, and 1990s include documentation of temporal declines in BOD_5 (Figure 7-10), ammonia-N (Figure 7-11), total nitrogen (Figure 7-12), and total phosphorus (Figure 7-13). Effluent reductions of oxygen-demanding loads from industrial and

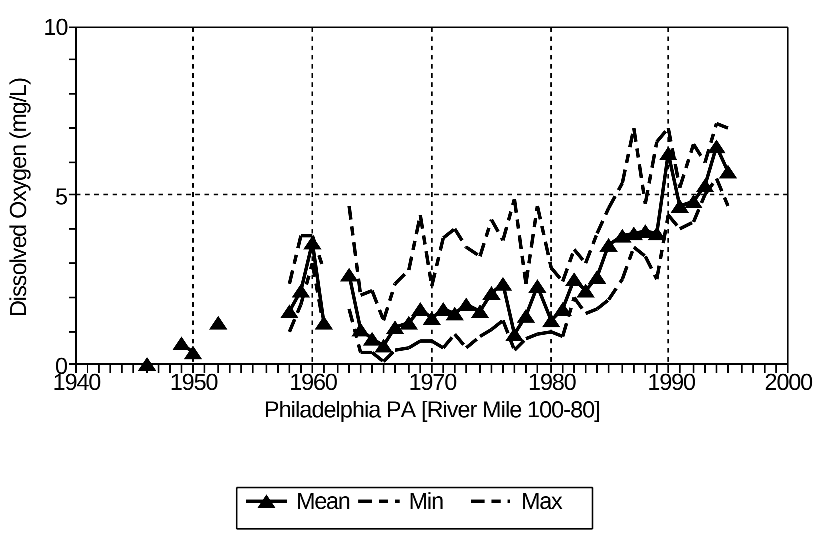


Figure 7-9

Long-term trends of summer (July-September) DO in the Delaware estuary near Philadelphia, PA (RF1-02040202030, mile 100-80).

Source: USEPA (STORET).

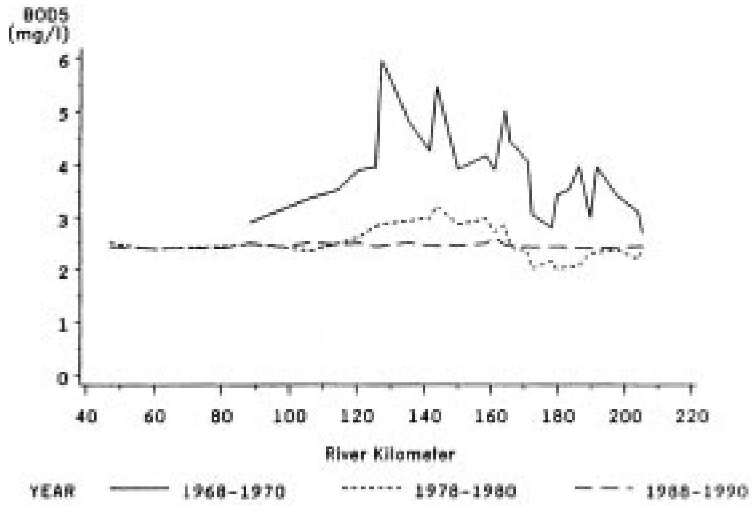


Figure 7-10

Long-term trends of the spatial distribution of BOD_5 in the Delaware estuary (mean of data from 1968-1970, 1978-1980, and 1988-1990).

Source: Marino et al., 1991.

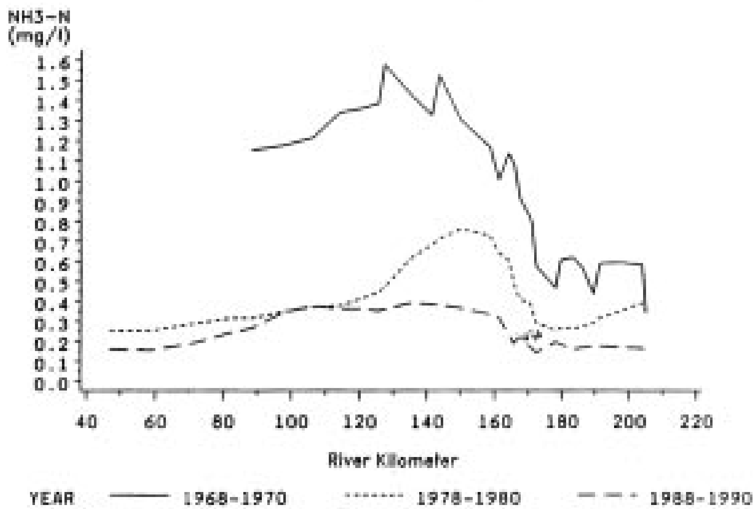


Figure 7-11

Long-term trends of the spatial distribution of ammonia-nitrogen in the Delaware estuary (mean of data from 1968-1970, 1978-1980, and 1988-1990).

Source: Marino et al., 1991.

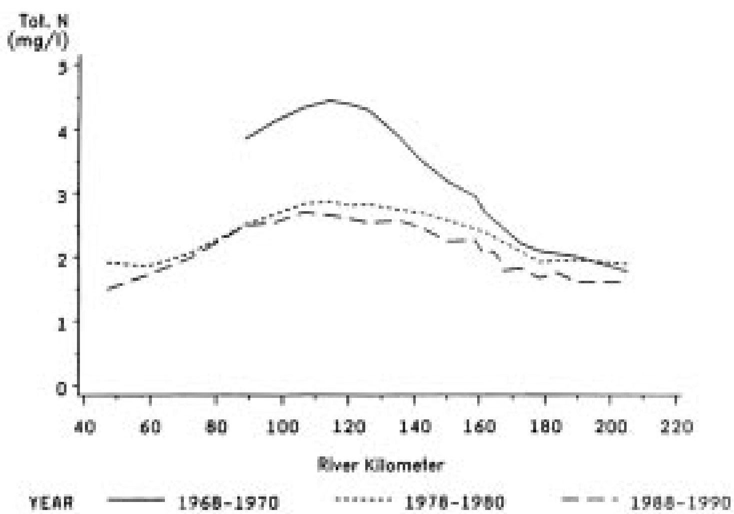


Figure 7-12

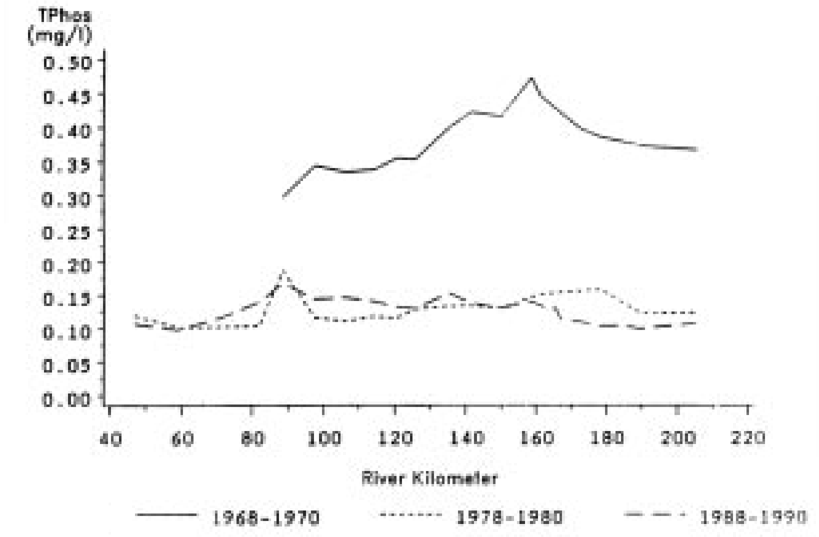
Long-term trends of the spatial distribution of total nitrogen in the Delaware estuary (mean of data from 1968-1970, 1978-1980, and 1988-1990).

Source: Marino et al., 1991.

Figure 7-13

Long-term trends of the spatial distribution of total phosphorus in the Delaware estuary (mean of data from 1968-1970, 1978-1980, and 1988-1990).

Source: Marino et al., 1991.

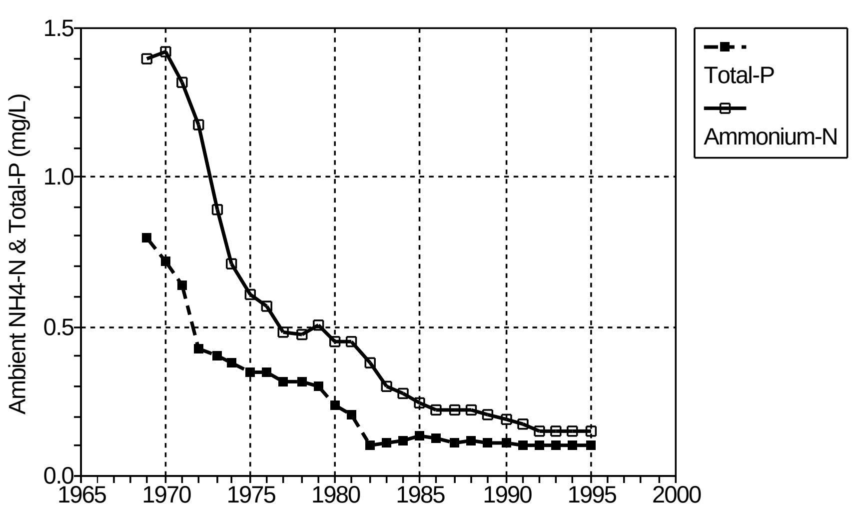


municipal sources have resulted in significant declines in ambient levels of BOD_5 and ammonia-N. An interannual temporal trend for ambient ammonia-N (Figure 7-14) at a station near Marcus Hook (RM 78) shows a considerable improvement in water quality, with a steep decline from approximately 1.4 mg N/L during the late 1960s to approximately 0.5 mg N/L by the late 1970s, followed by relatively unchanging ambient concentrations (approximately 0.15 mg N/L) recorded during the mid-1980s through the mid-1990s (Santoro, 1998). The decline in ambient ammonia-N during this 30-year period has been shown to correspond to a concurrent increase in nitrate-N from the mid-1970s through the mid-1980s as a result of nitrification (Santoro, 1998; Marino et al., 1991). Reflecting deforestation, agricultural practices, fossil fuel combustion, and the increase in human population of an increasingly urbanized drainage basin over the much longer time scale of a century, ambient nitrate and chloride levels (Figure 7-15) have steadily increased by approximately 400 percent to 500 percent since measurements were first recorded in 1905 at a water supply intake near Philadelphia (Jaworksi and Hetling, 1996). Similar patterns of long-term increasing trends in ambient nitrate

Figure 7-14

Long-term trends of summer ammonium-N and total phosphorus at a station in the Delaware estuary near Marcus Hook (mile 78) (computed as 4-year moving averages for July from DRBC boat run records).

Source: Santoro, 1998.



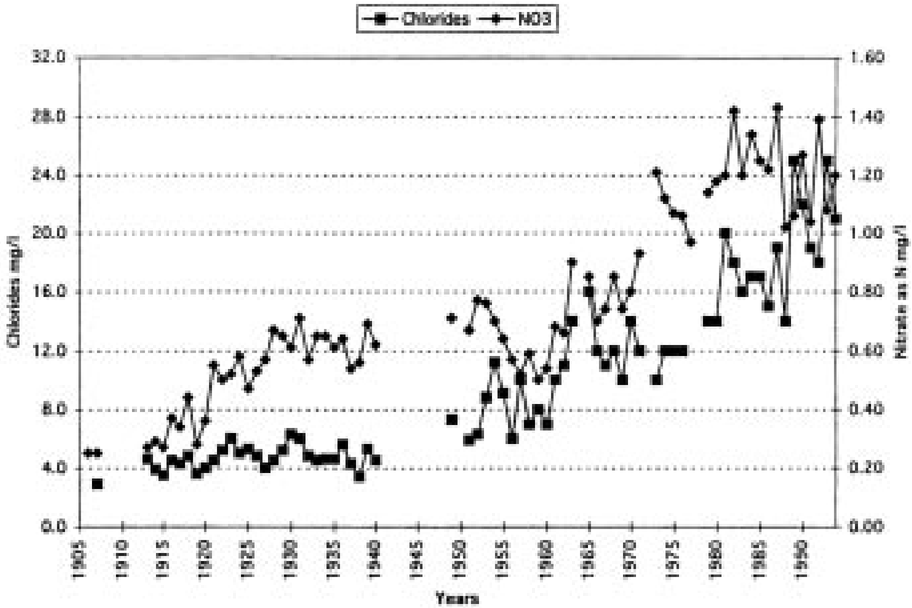


Figure 7-15

Long-term trends of chlorides and nitrate-N at a water supply intake in the tidal Delaware River near Philadelphia.

Source: Jaworski and Hetling, 1996; Jaworski, 1997.

and chlorides have also been recorded at other east coast water supply intakes for the Merrimack, Connecticut, Hudson, Schuykill, and Potomac rivers (Jaworksi and Hetling, 1996). Total phosphorus has also declined from peak levels of approximately 0.45 mg P/L during 1968-1970 to much lower levels of approximately 0.15 mg P/L by 1988-1990 near River Mile 100 (Figure 7-13). An interannual time series of total phosphorus (Figure 7-14) for a station near Marcus Hook (River Mile 78) exhibits a trend similar to that of ammonia-N with a sharp decline from approximately 0.8 mg P/L in the late 1960s to approximately 0.3 mg P/L by the late 1970s, followed by relatively unchanging concentrations (approximately 0.1 mg P/L) from the mid-1980s through the mid-1990s. The decline of ambient levels of total phosphorus has been attributed to the detergent phosphate ban of the early 1970s (Jaworski, 1997), reductions of effluent loads from wastewater facility upgrades (Sharp, 1988), and changes in partitioning of dissolved and soluble phases of phosphorus and changes in solubility of phosphate (Lebo and Sharp, 1993).

Evaluation of Water Quality Benefits Following Treatment Plant Upgrade

From a policy and planning perspective, the central question related to the effectiveness of the secondary treatment requirement of the 1972 CWA is simply *Would water quality standards for DO be attained if primary treatment levels were considered acceptable?* In addition to the qualitative assessment of historical data, water quality models can provide a quantitative approach to evaluate improvements in DO and other water quality parameters achieved as a result of upgrades in wastewater treatment. Since the early 1960s, four classes of water quality models, developed from the 1960s, through the 1990s, have been applied to determine waste load allocations for municipal and industrial dischargers to meet the needs for water quality management decisions for the Delaware estuary (Mooney et al., 1998).

During the 1960s, one-dimensional estuarine water quality models of DO and carbonaceous and nitrogenous BOD were developed by Thomann (1963), O'Connor et al., (1968), Pence et al. (1968), Jeglic and Pence (1968), and Feigner and Harris (1970). DRBC used a 1960s era model, known as the Delaware Estuary Comprehensive Study (DECS) model, to establish waste load allocations for ultimate CBOD and nitrogenous BOD for the six zones of the Delaware.

With funding available from the CWA Section 208 program during the 1970s, Clark et al. (1978) upgraded the kinetics of the water quality model to incorporate nitrification and denitrification in a nitrogen cycle represented by organic nitrogen, ammonia, and nitrate+nitrite as state variables. The oxygen contribution by algal production and respiration was included as an empirical input term dependent on chlorophyll observations. Transport was provided to the water quality model with one-dimensional link-node hydrodynamics, and the 1970s-era model was identified as the Dynamic Estuary Model (DEM) (Mooney et al., 1998).

As a result of industrial and municipal waste treatment plant upgrades from primary to secondary levels of treatment during the late 1970s and early 1980s, the water quality model used for waste load allocations was once again upgraded to reflect the reduced waste loads and improvements in water quality conditions (Mooney et al., 1998). The model was upgraded from a one-dimensional (longitudinal) to a two-dimensional representation (longitudinal and lateral) variation of water quality and transport in the Delaware estuary. A two-dimensional hydrodynamic model was coupled with a water quality model that retained the kinetic framework of the one-dimensional model with kinetic coefficients adjusted to reflect changes in pollutant loading (LTI, 1985). The upgraded 1980s-era two-dimensional model (DEM-2D) was used to conduct a toxics analysis (Ambrose, 1987) and to reevaluate the waste load allocations developed with the earlier models (DRBC, 1987).

Following the completion of the Delaware Estuary Use Attainability (DEL USA) Project (DRBC, 1989), a technical review of the two-dimensional DEM model recommended that a new time-variable model be developed to incorporate state-of-the-art advances, with a three-dimensional hydrodynamic model coupled to an advanced eutrophication model framework (HydroQual, 1994). Using revised kinetic coefficients to reflect reductions in waste loads and improvements in water quality, the kinetics of the water quality framework were expanded to include a eutrophication submodel, nitrogen and phosphorus cycles, labile and refractory organic carbon, and particulate and dissolved fractions of organic carbon and nutrients (HydroQual, 1998; Mooney et al., 1999). Unlike the eutrophication model developed for the Chesapeake Bay (Cerco and Cole, 1993), internal coupling of particulate organic matter's deposition with sediment oxygen demand and benthic nutrient fluxes was not included in the upgraded framework; benthic fluxes were assigned as model input on the basis of monitoring data (HydroQual, 1998).

To evaluate the incremental improvements in water quality conditions that can be achieved by upgrading municipal wastewater facilities from primary to secondary and better-than-secondary levels of waste treatment, Lung (1991) used the 1970s-era one-dimensional DEM model (Clark et al., 1978) to demonstrate the water quality benefits attained by the secondary treatment requirements of the 1972 CWA. Using the model, Lung used existing population and municipal and industrial wastewater flow and effluent loading data (ca. 1976) to compare water quality for summer flow conditions simulated with three management scenarios for municipal facilities: (1) primary effluent, (2) secondary effluent, and (3) existing wastewater loading. Water quality conditions for these alternatives were calibrated (Figure 7-16) using data for 1976, a year characterized by average summer flow of the Delaware River (see Figure 7-3). Freshwater flow at Trenton, New Jersey, was 7,700 cfs; flow in the Schuylkill River, a major tributary to the Delaware estuary, was 1350 cfs for the 1976 calibration. Flow conditions during the summer of 1976 were 120 percent higher than the long-term (1951-1980) summer (July-September) mean streamflow of 5,986 cfs recorded at Trenton. Upstream of Trenton, flow releases from several impoundments along the free-flowing Delaware River are regulated to maintain the guideline for a minimum summer streamflow of 2,500 to 3,000 cfs at Trenton (Mooney et al., 1998).

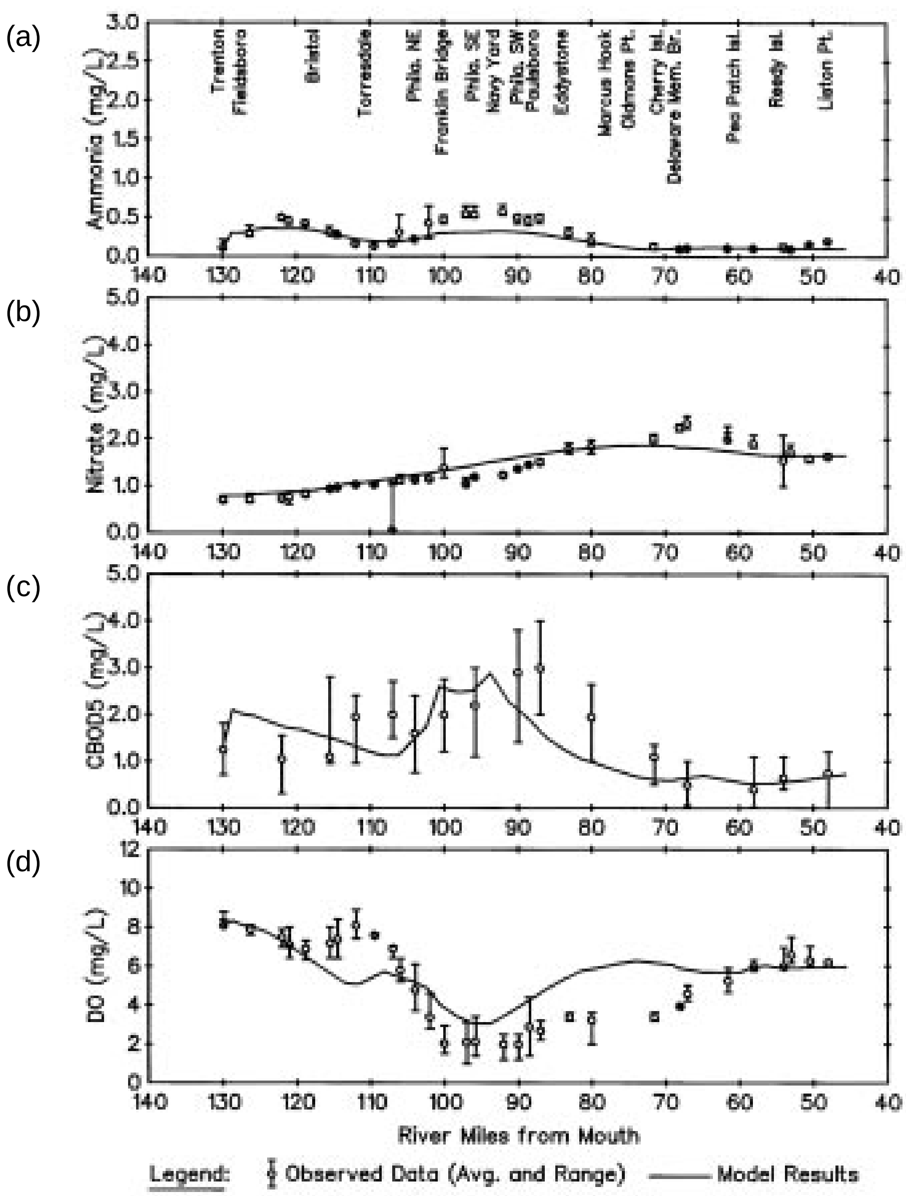


Figure 7-16

Model vs. data comparison for calibration of the 1-D Dynamic Estuary Model (DEM) for the Delaware estuary to July 1976 conditions for: (a) ammonia, (b) nitrate, (c) $CBOD_5$, and (d) DO.

Source: Lung, 1991.

Under the primary effluent assumption, water quality is noticeably deteriorated in comparison to the 1976 calibration results. DO concentrations are at a minimum about 35 miles downstream of Trenton, the traditional region of minimum DO levels. Under the primary scenario, an oxygen sag of 2 mg/L is computed by the model under summer (28EC), low-flow 7Q10 conditions (2,500 cfs for the Delaware at Trenton and 285 cfs for the Schuykill River at Philadelphia) (Figure 7-17).

Using the secondary effluent assumption, the reduction in ultimate CBOD loading significantly improves DO downstream of Philadelphia at the critical oxygen sag location (RM 96). In comparison to the primary scenario, minimum oxygen levels increased to almost 4 mg/L from approximately 2 mg/L under the

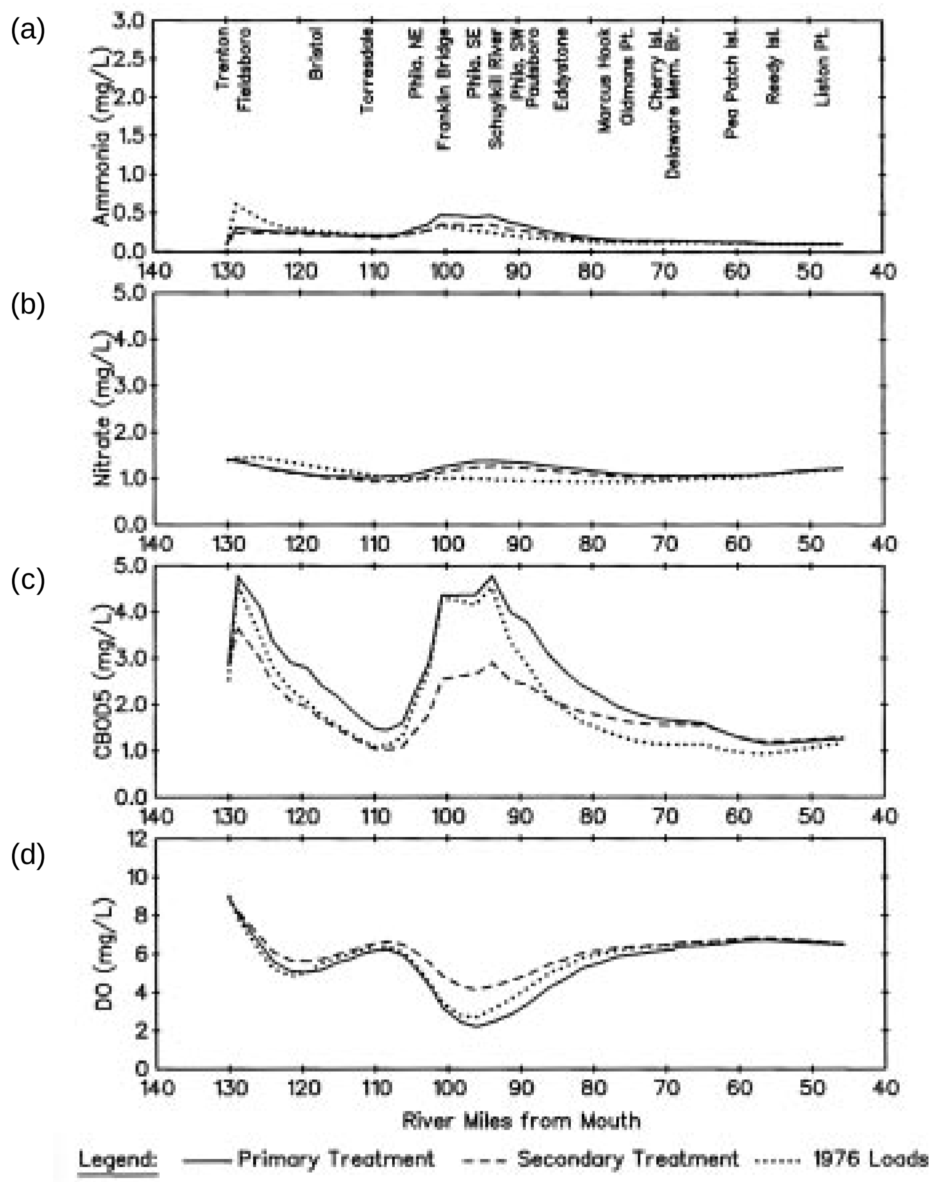


Figure 7-17

Comparison of simulated water quality impact of primary, secondary, and existing (1976) wastewater loading conditions on (a) ammonia, (b) nitrate, (c) $CBOD_5$, and (d) DO in the Delaware Estuary, July 1976 conditions.

Source: Lung, 1991.

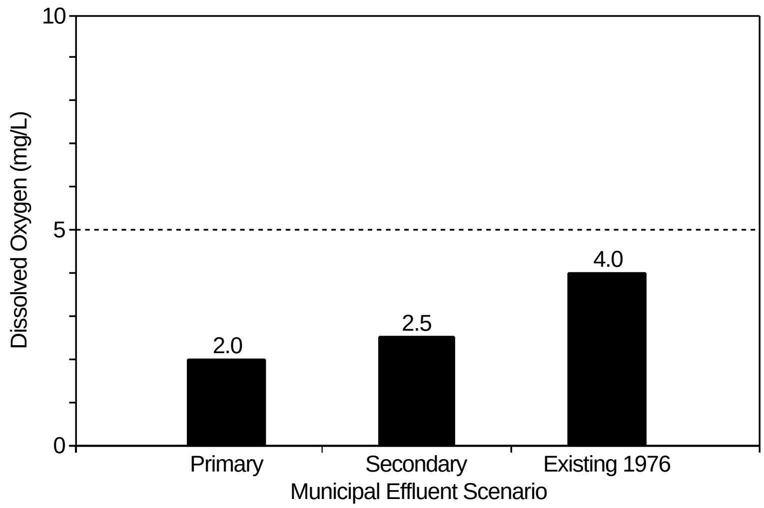


Figure 7-18

Model simulation of DO under July 1976 "normal" streamflow conditions at the critical oxygen sag location (mile 96) in the Delaware estuary for primary, secondary and existing (1976) effluent loading scenarios.

Source: Lung, 1991.

secondary effluent scenario (Figure 7-18). To achieve compliance with a water quality standard of 5 mg/L, advanced waste treatment is required (Albert, 1997). As shown with the historical water quality data sets, the implementation of secondary and better-than-secondary levels of wastewater treatment has resulted in major improvements in the DO, BOD_5, ammonia, and total phosphorus of the estuary (Figures 7-8 through 7-14). As demonstrated with the model, better-than-secondary treatment is required to achieve compliance with the water quality standard of 5 mg/L for DO downstream of Philadelphia. In contrast to the 1950s and 1960s, the historical occurrence of persistent and extreme low DO conditions has essentially been eliminated from the upper Delaware estuary. Improvements in suspended solids, heavy metals, and fecal coliform bacteria levels have also been achieved as a result of upgrades in municipal and industrial wastewater treatment.

Impact of Wastewater Treatment: Recreational and Living Resources Trends

With vast tidal marshes and freshwater tributaries providing spawning and nursery grounds for abundant fishery resources, the coastal plain of the Delaware estuary provided a cornucopia of fishery and waterfowl resources important for sustenance to both Native American villages and colonial settlements. Historically, the estuary produced an enormous quantity of seafood from the early colonial era (ca. 1700s) through the early 20th century. Colonial reports suggest schools of herring and sheepshead thick enough to walk on in a stream (Price et al., 1988). Rich harvests of American shad and shortnose sturgeon provided important sustenance to the growing population of the Delaware valley for about 200 years.

Since the mid-1900s, however, the abundance of these, and other, species has declined dramatically as a result of urbanization and industrialization of the drainage basin. Deterioration in water quality (e.g., severe oxygen depletion), overfishing, construction of dams, and habitat destruction have all contributed to the decline of the river's fisheries resources beginning around the turn of the century (Majumdar et al., 1988). Massive fish kills were a frequent occurrence along the river from about 1900 through 1970 (Albert, 1988). Former wetlands and tributaries, critical to the spawning success of anadromous species, have been converted into docks, wharves, industrial sites, and oil refineries (Stutz, 1992).

Decades of discharge of untreated municipal and industrial waste resulted in severe declines in the once-abundant fishery resources of the Delaware estuary. In 1836 commercial landings of the American shad (*Alosa sapidissima*), an important anadromous fish that spawns in the Upper Delaware River, were estimated at 10.5 million pounds. By the turn of the century, the average annual harvest of shad was 12-14 million pounds (Frithsen et al., 1991). Historically, the commercial shad harvest from the Delaware River fishery was the largest of any river system along the Atlantic coast (Frithsen et al., 1991). Primarily as a consequence of overfishing, water pollution and low levels of DO that created a "dead zone," construction of dams, and other obstructions in the river, shad populations declined drastically in the early 1900s (Frithsen et al., 1991).

In a pattern similar to that for shad, annual commercial landings of striped bass (*Morone saxatilis*) have also dropped from hundreds of thousands of pounds per year in the early 1900s to only thousands of pounds per year by 1960. In 1969 a fishery survey showed a complete absence of striped bass larvae and eggs along the Philadelphia-Camden waterfront, which had been an important spawning and nursery area for striped bass; by 1980 there was no commercial catch of striped bass (Himchak, 1984).

The historical abundance of shortnose sturgeon (*Acipenser brevirostrum*), once prized for caviar that rivaled imported Russian caviar, also followed the same precipitous decline as shad as overfishing and water pollution took their toll on this once-thriving fishery. Historically, the range of the shortnose sturgeon was from the lower Delaware Bay as far upstream as New Hope, Pennsylvania (RM 149) (Frithsen et al., 1991). Historical records from 1811 to 1913 document 1,949 sturgeon captured, primarily as a bycatch of the shad gill net fishery. During the period from 1913 through 1954, no documented catches of sturgeon were reported. From 1954 through 1979, 37 sturgeon were reported in fishery and ecological surveys. From 1981 to 1984, 1,371 sturgeon were collected between Philadelphia and Trenton (Frithsen et al., 1991). Using data collected from the early 1980s surveys, Hastings et al. (1987) have estimated populations of approximately 6,000 to 14,000 adult shortnose sturgeon in the upper tidal river near Trenton, with a smaller population estimated for the section of the river near Philadelphia (Frithsen et al., 1991).

Although it is difficult to assess the relative importance to these species of each of the major industrialization factors that contributed to the declines, Summers and Rose (1987) identified a connection between water quality, especially DO concentrations, and wastewater loading and shad population levels. Using records collected during the 20th century from the Delaware, Potomac, and Hudson estuaries, historical fluctuations in American shad populations have been strongly correlated with wastewater discharges that increased biochemical oxygen demand levels and depleted oxygen resources (Summers and Rose, 1987). Albert (1988) and Sharp and Kraeuter (1989) also noted the importance of good oxygen concentrations to successful shad migrations. Little correlation between water quality and striped bass populations was found, but Summers and Rose (1987) noted that larval survival for both shad and striped bass is tied to DO and other water quality factors.

Beginning in the mid-1970s, however, the water pollution control efforts of the 1970s and 1980s have paid off with a dramatic recovery of once moribund fishery resources. Estimates of the American shad population fluctuated from a low of 106,202 in 1977 to a high of 882,600 in 1992 (Santoro, 1998) (Figure 7-19). As a result of improvements in water quality conditions, the spawning area used by shad has increased by 100 miles in the estuary (Albert, 1997). Annual shad festivals are now celebrated in the spring along the Delaware River, and the recreational shad fishery is considered to be a multimillion-dollar industry (Frithsen et al., 1991). As a result of water pollution control efforts and a well-regulated fishery, populations of striped bass in the Delaware River are also showing evidence of a resurgence of once-depleted populations (Santoro, 1998). Assessments of commercial harvest statistics for American shad (Figure 7-20), striped

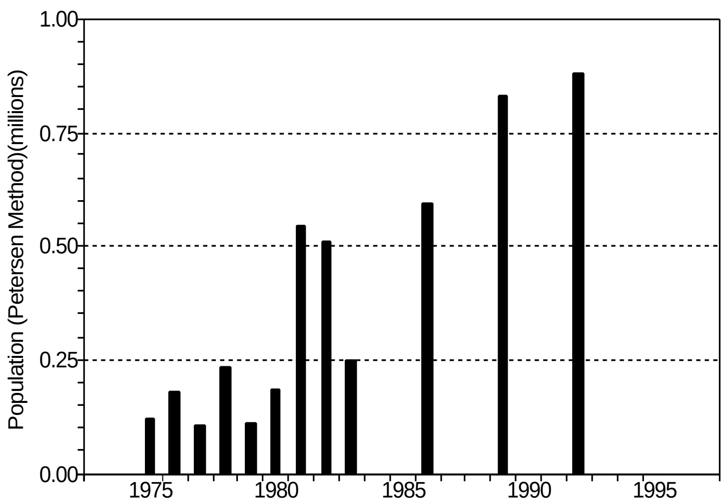


Figure 7-19

Long-term trends in population estimates of adult American shad in the Delaware estuary.

Source: Santoro, 1998.

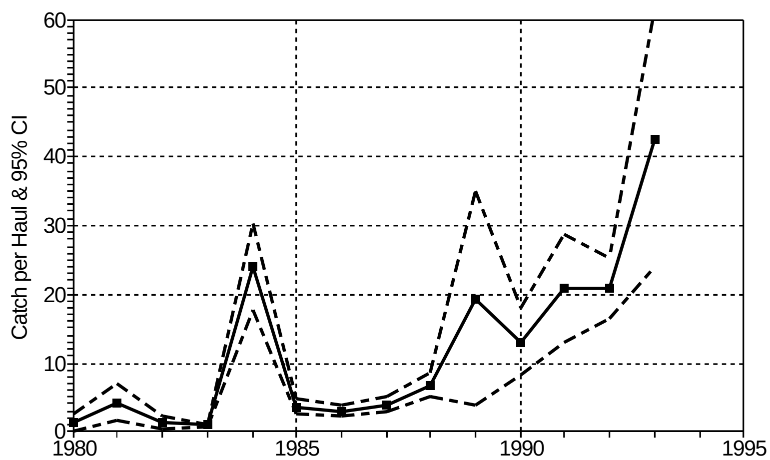


Figure 7-20

Trends in catch efficiency for American shad in the Delaware estuary.

Source: Weisberg et al., 1996.

bass (Figure 7-21), and white perch (Figure 7-22) clearly document significant increases in the catch-per-unit effort of these species from 1985 to 1993, correlated with improvements in water quality (Weisberg et al., 1996). Trends in catch efficiency are also reported by Weisberg et al. (1996) for blueback herring and alewives. Studies of the distribution and abundance of the shortnose sturgeon, listed as an endangered species (Price et al., 1988), suggest that populations may be recovering from the historical decimation of this species during the 20th century from water pollution and overfishing (Fristhsen et al., 1991).

In addition to pelagic fishery resources, the Delaware estuary has historically provided important harvests of American oysters, blue crabs, horseshoe crabs, hard clams, and American lobsters. Following a pattern identified in New York Harbor, a sharp decline in the harvest of oysters during the 1950s has been attributed to overfishing, sediment runoff and industrialization of the watershed, industrial and municipal wastewater discharges, oil spills, and spraying of marshes with DDT for mosquito control (Frithsen et al., 1991). In 1957 a parasitic organism (MSX) infected the oyster beds, drastically reducing abundance for decades.

Figure 7-21

Trends in catch efficiency for striped bass in the Delaware estuary.

Source: Weisberg et al., 1996.

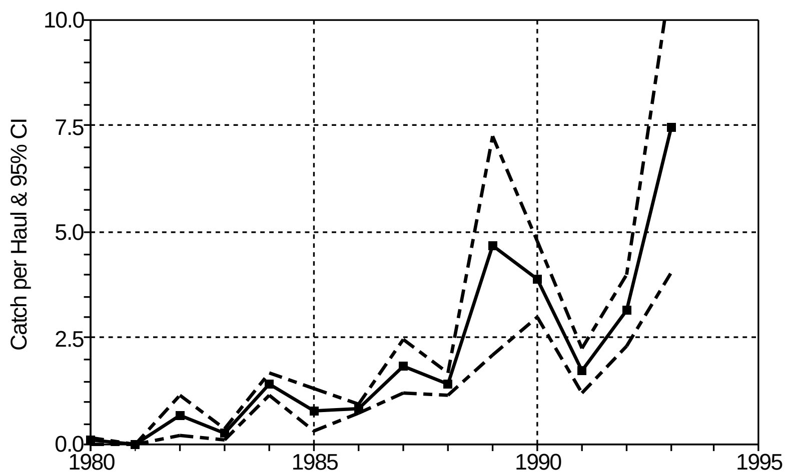
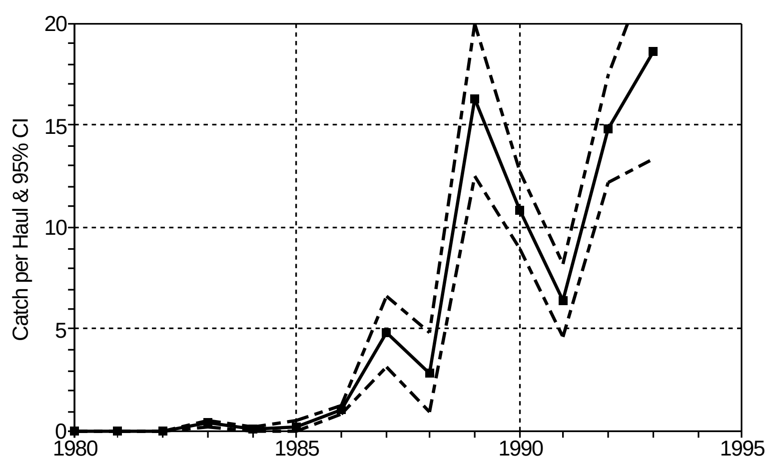


Figure 7-22

Trends in catch efficiency for white perch in the Delaware estuary.

Source: Weisberg et al., 1996.



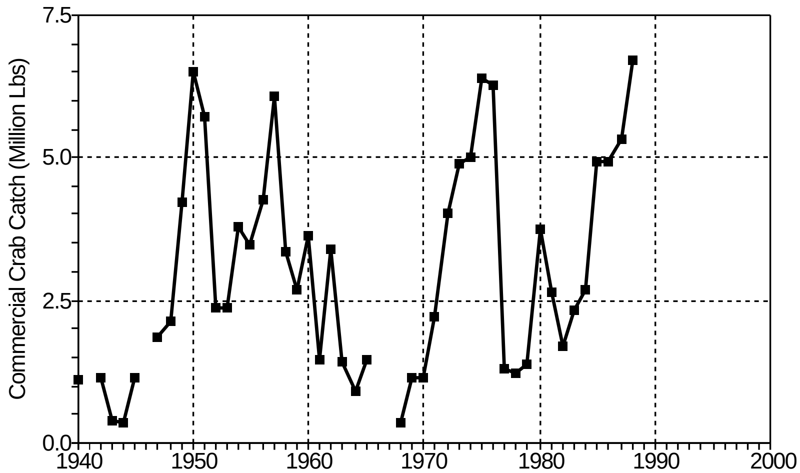


Figure 7-23

Long-term trends of commercial blue crab catch in the Delaware estuary (New Jersey and Delaware totals).

Source: Patrick et al., 1992.

With the decline of the oyster harvest, the blue crab catch has accounted for most of the shellfish catch of the Delaware estuary. During the late 1800s through the 1930s few blue crabs were harvested commercially. Since the 1930s, commercial landings have increased substantially, particularly during the 1980s (Figure 7-23), although large interannual variability in the Delaware estuary is characteristic of this species sensitive to water temperature (Frithsen et al., 1991). More detailed reviews of historical trends for the shellfish and fishery resources of the Delaware estuary are given by Price et al. (1988), Patrick (1988), Patrick et al. (1992), and Frithsen et al. (1991).

Summary and Conclusions

During the 1940s, 1950s and 1960s, the Delaware estuary was characterized by severe water quality problems, including the foul stench of hydrogen sulfide gas caused by anoxic conditions in sections of the river near Philadelphia. Uncontrolled wastewater discharges and destruction of habitat from urban and industrial growth in the Delaware watershed were responsible, along with overfishing, for the collapse of many historically important fisheries in the Delaware estuary such as American shad, striped bass, shortnose sturgeon, and American oysters. Desirable amenities such as parks, walking trails, or cafes along the riverfront were not considered for urban development because of the noxious conditions of the Delaware River.

As a result of water pollution control efforts implemented since the late 1960s in the Delaware estuary, dramatic reductions in municipal and industrial effluent discharges of ultimate CBOD, ammonia-N, total phosphorus, and fecal coliform bacteria have been achieved by upgrading wastewater treatment facilities to secondary and better-than-secondary levels of treatment. Municipal and industrial loading of ultimate CBOD to the river, for example, was reduced by 89 percent during the period from 1958 to 1995.

New construction and upgrades of municipal and industrial water pollution control facilities have resulted in significant improvements in water quality, the resurgence of important commercial and recreational fishery resources, and a renewal of economic vitality to once abandoned urban waterfronts along the Delaware River.

Assessment of long-term trends of historical water quality data at critical locations clearly documents great improvements in DO, ammonia-nitrogen, total phosphorus, and fecal coliform bacteria. DO, for example, has improved from typical summer minimum levels of less than 1 mg/L during the 1960s and 1970s along a 10-mile section of the river downstream from Philadelphia to minimum levels of 4 mg/L and higher during the 1990s. Ambient ammonia concentrations near Marcus Hook have declined by an order of magnitude from late 1960s levels of approximately 1.4 mg N/L to mid-1990s levels of approximately 0.15 mg N/L. Total phosphorus has exhibited a trend similar to ammonia's with late 1960s levels of approximately 0.8 mg P/L dropping almost an order of magnitude to approximately 0.1 mg P/L during the mid-1990s.

A number of indicators of environmental resources of the Delaware estuary have also demonstrated tremendous improvements that can be attributed to the water pollution control efforts and associated public awareness of the importance of environmental quality initiated by the 1972 CWA. The recovery of the American shad population during the mid-1980s, for example, is a remarkable achievement. The restoration of this important fishery resource to populations that can support an extensive recreational and commercial fishery is a remarkable success story. Highly popular annual shad festivals now celebrate the seasonal migration of this fish from the ocean into the estuary as a rite of spring.

Although the restoration of valuable fishery resources is important from an economic and ecological perspective, the recreational benefits achieved by the cleanup of the Delaware River far exceed the benefits attributed to fishery improvements. Riverfront development for commercial uses and public parks, increases in sailing and boating, and numerous other economic benefits have occurred along the Delaware River. Most remarkable is that the city centers of Philadelphia, Wilmington, and Trenton, after decades of urban development activity retreating inland, are now moving back toward the riverfront. Investments in urban development along the river would simply not be feasible without the aesthetic qualities of clean water (Albert, 1997). Urban waterfront and riverfront development activity has also been booming in many other cities (e.g., New York Harbor; Cleveland, Ohio; Boise, Idaho; Portland, Oregon; Atlanta, Georgia; Richmond, Virginia) that have successfully cleaned up polluted rivers, lakes, and harbors, making their urban waterways assets and sources of civic pride rather than disgraceful liabilities.

Despite the remarkable environmental improvements achieved by investments in water pollution control infrastructure since initiation of the 1972 CWA, challenges remain for the next generation. Water quality and resource management problems recognized only since the mid-1980s must be addressed. Contamination of the water column and sediments by heavy metals such as mercury, chromium, lead, copper, and zinc has been identified in urban-industrial areas of the river. Probable sources of heavy metals include natural geochemical processes, industrial and municipal dischargers, stormwater runoff, and atmospheric deposition (Santoro, 1998). Toxic chemicals such as PCBs, PAHs, and pesticides have also contaminated the water column and sediments of the estuary, resulting in bioaccumulation in benthic organisms. Fish consumption advisories were issued in 1989 by New Jersey and Pennsylvania and in 1996 by Delaware (Santoro, 1998). Acute sediment toxicity appears to be more widespread in the estuary than previously documented, with the highest areas of sediment toxicity identified in the heavily urbanized and industrialized region between Torresdale and Marcus Hook. Chronic toxicity was also identified in the water column under particular conditions of streamflow and effluent discharges (Santoro, 1998). The design and construction of facilities to control and treat combined sewer overflow discharges of raw sewage to the tidal river during heavy rainstorms is an ongoing project. Finally, the allocations of wastewater loads for ultimate CBOD from municipal and industrial dischargers that have evolved since 1968 will need to be revised to ensure that the water quality improvements achieved since the 1970s can continue to be maintained as population and industrial activity grow during the 21st century (Mooney et al., 1999; HydroQual, 1998).

In 1973 a USEPA study concluded that the Delaware River would never achieve designated uses defined by "fishable standards." More than 25 years after that pessimistic pronouncement, the fishery resources of the Delaware estuary are thriving. The restoration of the vitality of the estuary is a direct result of water pollution control efforts and strong public awareness of the importance of supporting federal, state, and local environmental regulations and policies.

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